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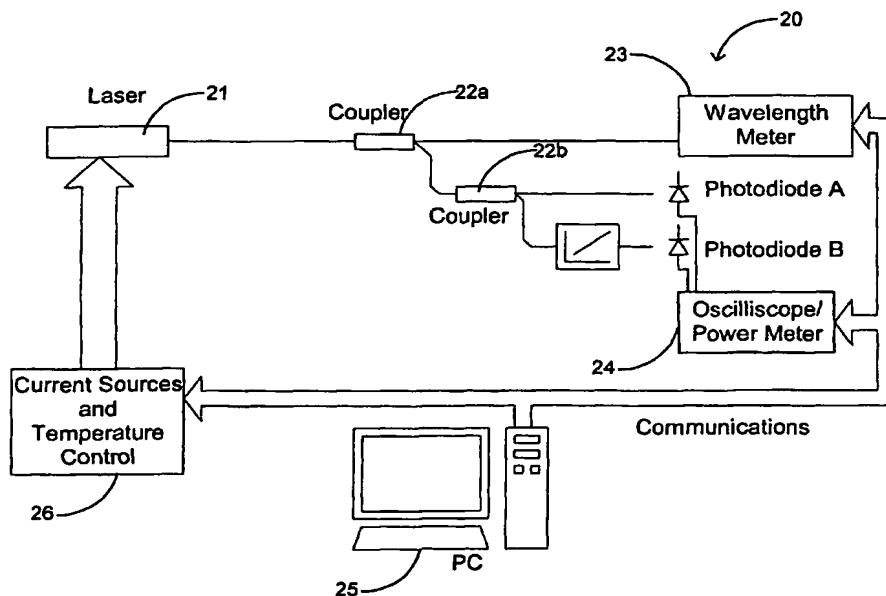
(57) Abstract: The invention provides a method and system for compensating variations in tuning efficiency and power of a multi-
section tunable laser diode. The invention comprises a means to obtain a set of values for a specific section of the laser diode and a
means to normalise the values to compensate the non-linearities in the set of values, hence compensating for variations in the tuning
efficiency for that particular section of the laser diode. The invention is advantageous in that it is generic and can be applied to
several different types of lasers. A further advantage of the invention is that the mode width can be determined as well as the mode
modulation of the tunable laser.

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Title

COMPENSATION OF MODE JUMPS IN TUNABLE MULTI SECTION LASERS

5   Field of the Invention

The invention relates to tunable lasers, particularly to a multi section laser diode that can be switched between different wavelengths or frequencies and more particularly

10   to a method and system adapted to compensate for variations in tuning efficiency and power of a laser.

Background to the Invention

15   Multi section laser diodes are well known in the art and can be switched between different wavelengths. Typically the diode is .calibrated at manufacture to determine the correct control currents that should be applied to the laser so as to affect the desired output frequencies from

20   the laser.

One of the first known multi-section laser diodes is a three-section tunable distributed Bragg reflector (DBR) laser. Other types of multi-section diode lasers are the

25   sampled grating DBR (SG-DBR), the superstructure sampled DBR (SSG-DBR) and the grating assisted coupler with rear sampled or superstructure grating reflector (GCSR). A review of such lasers is given in *Jens Buus, Markus Christian Amann, "Tunable Laser Diodes" Artect House, 1998*

30   *and "Widely Tunable Semiconductor Lasers" ECOC'00. Beck Mason.*

Figure 1 is a schematic drawing of a DBR 10. The laser comprises of a Bragg reflector sections 2 with a gain or active section 6 and phase section 4. An anti-reflection coating 9 is sometimes provided on the front and/or rear facets of the chip to avoid facet modes. The Bragg reflector take the form of Bragg gratings 5. The pitch of the gratings of the Bragg reflector vary slightly to provide a Bragg mode which moves in frequency through varying the current supplied to these sections. The optical path length of the cavity can also be tuned with the phase section, for example by refractive index changes induced by varying the carrier density in this section. A more detailed description of the DBR and other tunable multi-section diode lasers can be found elsewhere *Jens Buus, Markus Christian Amann, "Tunable Laser Diodes" Artect House, 1998.*

As detailed above such tunable semiconductor lasers contain sections where current is injected to control the output frequency, mode purity and power characteristics of the device. Various applications in telecommunications/sensor fields require that the laser can operate at points in a predetermined frequency/wavelength grid; moreover many applications require the power output of the device to be within a defined tolerance for each operating point, and in general, the operating points must be distanced from mode jumps and have high side-mode suppression. In order to provide lasers for such applications, each individual device must be characterised to the desired specification, so there is a corresponding need for a system or algorithm to map the output of the laser over a range of operating currents. For characterisation of lasers in production

environments, such a system must also be fast, reliable and automated.

The rate of change of the output frequency of the tunable laser for a given change in current is called the tuning efficiency of the laser. This parameter has the characteristic that it is not constant and tends to saturate at higher input currents. This variation can be quite considerable (greater than an order of magnitude) across the tuning range of the device. A consequence of this variation in tuning efficiency is that mode jumps in the tuning space of the laser may not be distributed linearly with drive current, which can cause problems for a calibration algorithm that is attempting to find the operating points of the laser with high mode purity.

A direct and accurate approach to measuring the tuning efficiency of a device, or to map the frequency output of the device, is to increment the section current(s) with which frequency changes and to accurately measure the frequency at each point. A problem with this approach, as described in "Fast Accurate Characterisation of a GCSR laser over the complete EDFA Band" *Tom Farrell et al. LEOS'99 November, San Francisco,* is that for certain device types, the tuning efficiency at low coarse tuning section current is very high, forcing a particularly low step size for this section. For example in the DBR (Distributed Bragg Reflector) laser, the tuning efficiency will be very high at low DBR passive section current. To apply this low step size over the entire operational range of the DBR section is time consuming. In production environments this approach is generally too inefficient to be commercially viable. Another problem of using a single step size over the

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operational range of the section current is that, since the data measured is varying non-linearly, a characterisation algorithm searching for features in the data (such as the mode boundaries) must find a means of coping with this non-

5   linear variation.

It is known that the output power of a device will fall off as the current in the passive sections is increased. Thus for measurements taken at fixed gain section current, the

10   operating points may not fall within the required range of specified power outputs. Thus combining a series of measurements at different fixed gain currents, where the passive section currents are ramped as before, may be needed to produce the final set of operating points

15   satisfying all the power, frequency and mode purity (SMSR) requirements. This of course adds extra time and analysis to the process, again an important issue in assessing the viability of a method for use in production environments.

20   There is therefore a need to provide a method and system that enables a compensation in the variation in tuning efficiency and power of the laser diode to be effected.

Mode width variations (modulation) has not been quantified

25   by anyone heretofore which can provide a parameter to give a qualification of the laser performance. A method of measuring the mode modulation of a tunable laser is desirable. This measurement is based on the variations in mode width of a tunable laser for different output

30   wavelengths of the laser. This measurement shows a clear performance characteristic of a tunable laser and the measurement for an ideal laser shows no mode width variation over the tuning range of the device. Mode width

variations (modulation) is caused normally by internal reflections between sections of the laser and is an undesirable effect. A problem with these reflections is that they produce an undesirable effect. The larger the mode width the more tolerant the device is to ageing effect. As the laser ages the mode positions will move due to a breakdown in the material. If the mode width is small the laser can only tolerate small changes in the mode position hence the larger the mode width the longer the lifetime of the device. It has not been possible to date to effectively measure the mode width to enable a user to determine the performance of a tunable laser.

Object of the Invention

It is an object of the present invention to provide a method and system for efficiently compensating for variation in tuning efficiency and power of a laser diode. Another object of the present invention is to provide a method to effectively measure the mode width and modulation of a tunable laser further increasing the tuning efficiency and power of a laser diode.

Summary of the Invention

Accordingly the present invention provides a method of compensating for variation in tuning efficiency and power of a multi-section tunable laser diode. The methodology and system as set out in the appended claims is advantageous in that it is generic and can be applied to several types of tunable lasers such as DBR, SG-DBR, SSG-DBR, GCSR etc.

In a preferred embodiment the invention provides a method
and system of normalising the output values of a laser
diode, the method comprising the steps of varying the
control currents for a specific section of a laser diode
device over a range of values in a first sample index so as
to obtain a set of output values for that section of the
laser diode, normalise the set of output values, such that
the normalisation of the output values compensates for non-
linearities in the output values by effecting a change in
relationship between the control currents and the sample
index.

The advantage of the present invention is that the
measurements are performed on a linear output wavelength
axis rather than input current to the laser. This provides
a better sampling resolution and any features in the data
such as mode jumps occurring at a fixed wavelength tuning
rate.

Another advantage is that the output power equalisation of
the output light from a laser can be performed in a much
easier fashion by adjusting the output power to compensate
for losses in the laser due to increased current in the
tuning sections of the laser.

The output values are desirably representative of power or
frequency.

The method may be further used to obtain sets of normalised
values for one or more further sections of the laser.

The normalisation is desirably effected by a transform
applied to the sample index, the application of the

transform changing the control currents and the output values. The transform is typically a non-linear transform.

The generated transform may be subsequently used to effect the generation of a further set of output values for multiple combinations of control currents or sections for the laser device, the generated set having being normalised due to the utilisation of the transform.

In one embodiment, the normalisation of the output values is effected using the current of the mode jumps.

The mode jumps are typically detected by a power measurement, and are more typically detected by an observation of discontinuities in a power measurement.

In an alternative embodiment the mode jumps are detected by a frequency measurement, and in such an embodiment are typically represented by a step in a frequency measurement.

The application of the transform may be used to effect an equalisation of mode width.

The method may be further used to determine deviations in mode width, thereby providing indications of the integrity of the laser device.

The normalisation may be effected using a relative loss of that section as a function of control current. The gain current of the laser device can be altered using said normalisation.

The normalisation of output values may be used to provide for a determination of location of modes.

The method may include the further step of determining suitable operating points, the operating points being selectable on the basis of a determination of a mid-point in frequency values for a specific mode. The operating point is typically at the mean frequency for that mode and benefits from maximum side mode suppression.

The modes are desirably locatable by effecting a differentiating of the normalised values.

The invention also provides for a method and system of determining a mode width for a laser diode device, the method comprising the steps of: determining the location of the modes, extracting from the determined mode locations, the mode width in control current as a function of a control current for all modes and all currents so as to provide for a relationship between the mode width of the laser and a control current for that laser, and converting the control current to frequency for the device so as to provide a relationship between mode width and frequency.

The invention also provides for a method and system of obtaining the mode modulation of laser diode, the method comprising steps of obtaining tuning characteristics of a tunable laser and measuring a set of samples where this data has been normalised out, detecting mode jumps of the laser, measuring the mode width of the laser and plotting this value against a predetermined combination of the control currents where this mode is present which can in turn be converted to output frequency of the tunable laser,

and converting the mode width to a percentage deviation of average mode width of the laser.

Another advantage to measuring the mode width modulation is that this is proportional to the side mode suppression ratio (SMSR) of the laser output, which quantifies the spectral purity of the output laser light. This is an important quantity for most systems these lasers are used in. The advantage of using this method to estimate the SMSR is that SMSR measurements are quite slow and with this method the measurement can be performed over one hundred times faster than conventional techniques.

There is also provided a computer program comprising program instructions for causing a computer program to carry out the above method, which may be embodied on a record medium, carrier signal or read-only memory.

These and other features of the present invention will be better understood with reference to the following drawings.

Brief Description of the Drawings

Figure 1 is a schematic drawing of a known laser diode,

Figure 2 is a schematic showing a conventional wavelength measuring apparatus and control system,

Figure 2a shows the output power of a device at uniform current intervals in the direction that the tuning efficient variations are to be suppressed,

Figure 2b shows the output power range of Figure 2a, but with the effects of the tuning efficiency variation suppressed,

5   Figure 3 shows a high-resolution power line as taken along a full range of DBR passive current sections and at a constant phase current and also indicates the position of mode jumps,

10 Figure 4 is a graphical representation of a polynomial correction tuning efficiency approximation, according to the present invention,

Figure 5 is a graphical representation of polynomial scaled
15 to a desired sample and current range according to the present invention,

Figure 6 is an example of a linear power plane,

20 Figure 7 is an example of a non-linear power plane over the same range of values as Figure 6, as provided by the methodology of the present invention,

Figure 8 is a plot of mode width verses bragg current for a
25 laser diode device with mode modulation,

Figure 9 is a plot of mode width variation verses frequency for a laser with mode modulation,

30 Figure 10 is a normalised version of the plot of Figure 9 with the % mode width variation converted to frequency modulation,

Figure 11 is an intensity map of power vs two control currents of a tunable laser mapped onto a Power vs. Total control current map,

5   Figure 12 shows a plurality of curves representing the loss of the front and back gain currents for a plurality of different gain currents, and

Figure 13 is a plot of gain current verses front and back
10   current showing the required ratio between the parameters required to effect a desired power level for the device.

Figure 14 shows a series of operating points in the center of mode jump free regions denoted by the dots.
15

Figure 15 shows a plot of the operating points shown in figure 14 plotted as front current of mode center vs. mode index where mode index is the number representing each mode center starting from zero and incrementing by one.
20

Figure 16 shows a plot of the operating points shown in figure 14 plotted as back current of mode center vs. mode index where mode index is the number representing each mode center starting from zero and incrementing by one.
25

Detailed Description of the Drawings

The present invention provides a method of compensating for inefficiencies in tuning and power of a laser diode,
30   specifically a multi-section tunable laser diode. The technique is generic and can be applied to several types of tuneable lasers such as DBR, SG-DBR, SSG-DBR, GCSR etc., although for ease of explanation it will now be described

with reference to application to a DBR tuneable laser. It will be appreciated by those skilled in the art that this illustration is exemplary of the methodology of the present invention and it is not intended to limit the application to any one specific laser diode type.

The techniques used by the method of the present invention enable the formation of a set of output values, typically a power or frequency plane, which will be understood to be a series of power or frequency measurements at section current combinations within a specified range.

Referring now to Figure 2 there is illustrated a typical control system to implement the present invention generally indicated by the reference numeral 20. A laser 21 has an output connected to a coupler 22a, which in turn is connected to a another coupler 22b. The output of the coupler 22a, 22b are in communication with a wavelength meter 23, oscilloscope 24, a computer apparatus 25, for example a PC, and a current source temperature control device 26. This control system 20 provides a means to vary the control currents for a specific section of a laser diode device over a range of values in a first sample index so as to obtain a set of output values for that section of the laser diode and means to normalise the set of output values wherein the normalisation of the output values compensates for non-linearities in the output values by effecting a change in relationship between the control currents and the sample index. Typically the use of this type of control system can be used for the testing of laser devices prior to using such devices in any system for example telecommunications or instrumentation systems.

Using the technique of the present invention it is possible to provide for a more evenly spaced distribution of modes in the resultant data set which is advantageous in that it enables simpler and more effective analysis techniques. The
5 method of the present invention also provides for a reduction in the size of the data set that requires analysis, thereby providing a more time and processing efficient system.

10 The methodology of the present invention will now be described with reference to a three section DBR type laser device. Firstly, a method to obtain the characteristics, preferably the tuning efficiency as provided by the frequency or power output, of the laser according to the
15 present invention will be described. Using the resultant data set, the invention then provides for a technique to use this data and measure the characteristics of the laser while canceling out the tuning efficiency variation and the power loss due to increasing currents in the passive
20 sections. An exemplary application of the technique will then be described with reference to a specific device

1. Automated Approximation of Laser Tuning Efficiency:

25 As detailed above, the present invention provides a methodology to determine a function to approximately map the tuning efficiency of the laser. It should be noted that according to the present invention, the tuning efficiency function is only required to determine a suitable set of
30 sample to section current mappings; consequently the tuning efficiency itself is not required to any great accuracy, but it will be appreciated can be obtained accurately from measurements described in this patent application, and

moreover measurements over a subset of the current space of the tunable laser are sufficient. This it will be appreciated provides for a time-efficient technique. For example, within a DBR laser, this subset would span the
5   range of the DBR passive section current only, with the phase section current set at a constant value.

Although the present invention is not intended to be limited to any one specific theory or methodology it will
10 for purpose of discussion be assumed that all that is needed to form a reasonably accurate approximation to the tuning efficiency of any device is the location of each mode jump of interest and the further assumption that frequency change across each jump is approximately uniform.
15 To obtain each mode jump, a straight line is defined across passive section current space, which may be a function of one or more section currents. A series of power measurements is obtained along this function over small increments in current. The data is then discretely linearly
20 filtered and thresholded to extract each mode jump.

This information, combined with the assumption that the frequency change across each mode jump is uniform, enables the mapping of approximately uniform steps in frequency to
25 non-uniform steps in section current. If one has access to frequency data, however, or to a measure that varies in proportion with the frequency across the subset of section currents of interest, this may be utilised to form an equivalent mapping. As a result, it will be appreciated
30 that the extraction of mode jump locations may not always be required.

Each set of discrete mappings or transforms is plotted for each contributing passive section. Since each plot consists of discrete value mappings, one may choose to either interpolate between defined mappings or to define a continuous function, which, in a least squares sense, fits the defined mappings optimally. The user may then specify the subsection of currents which are of interest and the amount of power plane samples which are desired within that region. Each passive section function can then be scaled accordingly, and the resulting mappings used to define locations in section current which correspond to each power plane sample. The resulting power plane is then predominantly free of the effects due to tuning efficiency variation.

2. Use of Non-Linear Power Planes:

This method has been developed as the first step in a tunable laser calibration system, and is specifically adapted to compensate for the variations on output power of the device due to increasing losses in the passive sections which is cause by increasing the control currents of the laser so as to provide for the modes jumps to be represented by similar jumps in output power of the device, and thus more easily determined. The control system, for example as illustrated in figure 2, calibrates each device based upon power/frequency measurements obtained at section current combinations within a pre-defined range of currents. It will be appreciated that the system and methodology is not device specific, although, as stated above, the straight line over which mode frequency changes occur will vary in terms of the section currents from device to device.

It will be understood therefore that for some devices, for example a SG-DBR type laser, non-linear power sampling may be required across more than one section current. In figure 14 a power plane for an SG-DBR laser is shown. A supermode

5   is selected and the centre of regions where the output power has no mode jumps is selected and these points are denoted by dots. If as for a DBR laser the current at which these points occur is plotted against the mode index the graphs Figure 15 and Figure 16 are obtained for the Front

10   and the Back sections of the laser. These represent the tuning rates of these sections and can be used in a similar way to that shown for the DBR laser.

It should be noted that a similar method can be used for a

15   phase section of a laser also by plotting the position of a mode as a function of phase current and using a non-linear sampling rate to cancel any non-linear tuning of the phase section when measuring multiple planes.

20   <u>Benefits of Removing the Effects of Tuning Efficiency</u>

Variations: The main benefit of removing the effects of tuning efficiency variations across the device, is to maximise the efficiency of a subsequent calibration

25   algorithm with regard to the fact that each mode is represented by a uniform amount of points in the power plane, and that number is set as low as possible without compromising accuracy, i.e. that no mode is represented by too many or too few points. The advantage of the technique

30   of the present invention is evident from a comparison of Figures 2a and 2b.

Fig. 2a displays the output power of a device at uniform
current intervals in the direction that tuning efficiency
variations are to be suppressed (linear power line). Fig.
2b displays the output power across the same range, but

5   with the effects of tuning efficiency variation suppressed
(i.e. a non-linear power line as provided by the technique
of the present invention). It will be appreciated that a
mode jump should be distinguishable by a discontinuity in
power or frequency. It will be apparent from an inspection

10   of the two Figures, that there is a large variation in the
distance between mode jumps in the linear line relative to
the non-linear line (Figure 2b). Although both lines
contain the same amount of power samples, it is clear that
there are not enough samples in the linear line to easily

15   extract important signal characteristics at low currents.
However, the equivalent data in the non-linear power line
is easily extractable.

Another benefit of removing the effects of tuning

20   efficiency variations across the device is that each point
midway between two mode jumps (an instance of which is
marked as the vertical line X-X in Fig. 2b) will also be
the centre of its tuning range. This means that the point
will be at the mean frequency for that mode, and will

25   benefit from maximum side mode suppression. This makes it
an ideal choice as the operating point for that mode.

Measuring Frequency Modulation of a Laser using Mode Widths

30   As described previously the mode width (in current) at
relative tuning currents in the laser describes the
relationship between tuning rate and current(GHz/mA). It
will be appreciated that the Mode Width is proportional to

tuning rate vs. tuning current, which can be understood in terms of the Bragg current as meaning that the width of the mode in Bragg current is the relative size of the reflection peak that is causing the laser to operate at this frequency relative to the adjacent modes of lasing of the laser.

Using this relationship it is possible to obtain a plot of mode modulation of the laser. Mode modulation is caused by extra Fabry Perot cavities existing in the laser and is normally due to an undesirable reflection at the interface between the individual sections of the laser. These reflections when added to the desired reflections from the Bragg etc.. cause a modulation in the mode width of the laser.

The example below is shown for a DBR laser but the same method can be equally applied to any type of tunable laser.

From a plot of DBR power (where the tuning currents have been normalised out, such as that shown in Figure 7) a plot of the mode jumps of the laser can be obtained by using differentiation and a threshold to obtain where steps in power occur. These steps in power represent the mode jumps of the laser and are shown in Figure 17

From this plot (Figure 17), if the mode jump width (in Bragg Current) is extracted as a function of Bragg current (where Bragg Current is the current in the middle of the mode where each mode width is measured) for all modes and all phase currents and a plot, such as that shown in Figure 8, is obtainable which provides for a graphical representation of the mode width of the laser vs. Bragg

Current. As can be seen from the graph of Figure 8, this is
a very uniform result and shows that the mode modulation is
dependent directly on the Bragg current of the laser. This
can be related directly to Frequency by converting Bragg
5   current to Frequency with the aid of a plot of the tuning
rate of the Bragg Section. Such a plot is shown in Figure 9
and can be obtained by some wavelength measurements such as
a wavelength meter or equivalent or, as previously
described by obtaining a plot of mode position vs Bragg
10   current and sampling some frequencies either using a
wavelength meter or using the setup as in Figure 2.

The plot of Frequency vs. Bragg is true for any points on
all lines in-between each adjacent mode jump. As the laser
15   has mode jumps the tuning away from each of these lines
will be slightly different and a factor is required which
is the relative frequency tuning range of a single mode of
the laser for a fixed phase current. These values change
from device to device but an exemplary DBR laser device may
20   have values of the order of 12 GHz and the cavity mode jump
is 70 GHz. Therefore, the factor we require is 12/70. If we
multiply the frequency variation plot from above by this
factor the frequency modulation of the device is obtained
versus the absolute frequency of the laser. This is a
25   relative value and shows deviations from the ideal uniform
performance of the laser.

In Figure 10 the mode modulation is caused by a reflection
between the gain section and the phase section of the laser
30   and the period of modulation is approximately 125 GHz. This
corresponds to a cavity length in the device of approx 340
μm which is as expected.

This measurement is a very good detector of internal reflection in the tuneable laser and can be obtained from a simple power plane of a tuneable laser. This measurement is fast and can be used in the characterisation of tuneable lasers in a production environment. As the result obtained can be easily thresholded to detect when the internal reflections are too large the device will not meet the required specification it is ideal for Pass/ Fail criterion required in an automated production system.

Measuring Power Loss Due to Increasing Currents in the Passive Sections:

All tuneable devices suffer power loss due to increasing currents in the passive sections. An objective of device calibration is to not only obtain operating points at pre-defined frequencies within the device band, but to ensure those points are of a certain output power level. Based upon an assumed relationship between power loss and passive section currents, the input gain current may be increased in such a way as to counter the loss.

The example below is for an SG-DBR laser but applies equally for a DBR laser, GCSR, SSG-DBR and other multi-section tuneable lasers.

If a coarse measurement of output power is measured on an SG-DBR laser and the output power is plotted against front current plus back current then a graph such as that in figure 11 is obtained.

This shows how the output power of the device varies as a function of the passive current (excluding the phase

current). If this plot is curve fitted to obtain the median output power (or some such other method is used such as averaging as shown in the figure 12) a curve which represents the loss of the front and back sections is

5   obtained. If this is repeated for different gain currents a set of these curves can be obtained as in figure 12.

It is possible then, using this information, to select the output power required to operate the laser. This selected

10   power will cut or bisect several of the curves obtained at each gain current in Figure 12. By plotting the gain current value from each curve against the front and back current value, a plot of gain current vs. Front and back current is obtained for the required output power value as

15   shown in Figure 13. This plot enables determination of the ratio between front and back current verses the gain current required to obtain the required power level. This can be fitted with a linear or higher order polynomial or such method to get the relationship and a power plane can

20   be re-measured where the gain current at each point on the plane is adjusted according to this relationship. This results in a power plane which will typically have 2dB of power variation as opposed to the 6dB for the case where the gain current is kept constant.

25

Using this technique to reduce the output power variation of a tuneable laser measurement plane enable power equalisation to be obtained in a much easier fashion as a large part of the power variation has already been

30   compensated for. Also this allows easier detection of changes in the power level which denote mode jumps of the laser. As the power variation is reduced the variation in

these jumps of power will be similar in size and allow easier detection.

3. Example:

The techniques of the present invention described above will now be described with reference to an example of tuning efficiency approximation for a DBR tuneable device. As was shown in Figure 1, this is a three section device, with two passive sections, phase 4 and DBR 2, and an active section, gain 6. In this particular type of device, mode jumps tend to occur with increasing DBR passive section current. Hence, a high-resolution power line was taken along the full range of DBR current and at a constant phase current (Fig. 3), and the location of mode jumps identified. The sample control system as illustrated in Figure 2 calibrates each device based upon power/frequency measurements.

As shown in Figure 4, this data may be used to plot a DBR current versus frequency index relationship (each unit increase in value represents a uniform jump in frequency). A 2nd order polynomial function was then fitted to this data, bound by its upper and lower limits. Both the original data and the fitted polynomial function are shown in Fig. 4. The fitted function for the specific data set illustrated is defined below:

$$f(x) = 0.1123x^2 + 0x + 0.0366, \quad (1)$$

where x is the frequency index of the data. This it will be appreciated is a standard quadratic polynomial which maps uniform steps in frequency to non-uniform steps in section

current across the full range of the device. In order to perform a full characterisation of the device, a subset of this entire range, i.e. a region of specific interest in both passive sections is then specified, along with a desired power plane size: i.e. how many data points are required for a specific range of currents. This range may be specified in terms of the maximum and minimum currents (I_{high} and I_{low}). Using a specific example of utilising 300 power samples on the DBR passive section in the range between 0.99 and 45.09 mA inclusive, it is possible to transform the fitted function, defined by equation (1) into a sample index to section current value mapping, based upon this specified data. The function transformation is defined below (equation (2)), and it will be appreciated that the present invention is not intended to be limited to any specific values or polynomial function. It will be further noted that $f^{-1}(I_{low})$ is x at $f(x) = I_{low}$, and that the equivalent stands for $f^{-1}(I_{high})$ (see Fig. 3 for the mapping between each x value and I_{low} & I_{high}).

$$f(s) = \left(a \times \left(\frac{m}{k}\right)^2\right)s^2 + \left(\left(\left(2 \times a \times f^{-1}(I_{low})\right) + b\right) \times \frac{m}{k}\right)s + \left(\left(a \times f^{-1}(I_{low})^2\right) + \left(b \times f^{-1}(I_{low})\right) + c\right)$$

(2)

where: a = x^2 coefficient in $f(x)$.

            b = x coefficient in $f(x)$.

            c = offset in $f(x)$.

            I_{low} = the lower threshold of the passive section current region of interest.

            I_{high} = the upper threshold of the passive section current region of interest.

            m = $f^{-1}(I_{high}) - f^{-1}(I_{low})$.

            k = No. of sample periods across mapping range.

            s is the sample index.

Substituting the values specific to this example for the above, yields the polynomial defined in Equation (3) below, and plotted in Fig. 5:

$$f(s) = 0.00037s^2 + 0.03741s + 0.9872 \quad (3)$$

The solving of this polynomial maps each of 300 sample points to a section current within the specified range, based upon the original mapping function, $f(x)$ (equation 1). Since tuning efficiency does not vary significantly with phase section current, the mapping between sample index and section current remained linear, and hence a uniform step size was used between power samples. It is now possible to utilise the sample index to current mappings for each passive section in the measurement of a power plane.

It will be appreciated that there are other such methods to achieve the same result as the equations show above, for example using a conversion from current to wavelength ro frequency for each of the laser sections. This may be measured in the example provided as shown or other such methods to achieve the same result.

It will be appreciated that equations 1,2 and 3 can be implemented in a computer program or software for example C++ or visual basic in order to implement various aspects of the present invention, however it will be understood to the person skilled in the art that any computer program maybe used. It will be further appreciated that various aspects of the present invention could be implemented in a

Field Programmable Gate Array (FPGA) or other logic hardware implementation.

Shown in Figs. 6 and 7 is a comparison between a 300 × 300 linear power plane over the range of DBR currents described by the function of equation (3) and shown in Fig 5, and a non-linear plane over the same range of currents. The plane of Figure 6 is formed using conventional techniques such as those described in "*Fast Accurate Characterisation of a GCSR laser over the complete EDFA Band*" *Tom Farrell et al. LEOS'99 November, San Francisco,* whereas that of Figure 7 is formed using the technique of the present invention. The relative uniformity of the width of each mode in the non-linear plane (Figure 7) is apparent especially when compared to the linear plane (Figure 6).

It will be appreciated that the specific example utilising a DBR type laser device enables the power plane characterising the device to be effected on a single measurement set. In application of the technique to other laser types it will be appreciated that several measurements may be required to fully characterise the device. For example using a SG-DBR device it is necessary to measure the output power vs. all of the coarse tuning currents, and for a 4-section SG-DBR laser this results in a plane. These measurements are repeated as a function of any other tuning sections that the device may have. For example with an SG-DBR laser several planes are measured of Front grating vs. Back grating against phase current.

It will be appreciated by those skilled in the art that although the example of the present invention has been described with reference to specific mathematical equations

and techniques that many alternative techniques may be utilised to obtain the same effect or implementation as that provided by the specific example herein illustrated.

5   For a person skilled in the art hysteresis can be represented in a similar method to that of mode modulation. This means that the hysteresis of the mode jumps as a percentage of the mode width can be plotted as a function of the wavelength of the laser, where the wavelength of the

10   laser is the output wavelength exactly in between the mode jumps. This allows an improved quantitative method of representing this effect similar to that of mode modulation.

15   It will be understood that the present invention provides for a method that compensates for tuning efficiency in a laser diode device, by providing a technique that enables a different sampling rate to be applied in different regions of interest in the power plane of the device.

20

It will be appreciated that the present invention provides for the provision of a graph of the relative tuning rates of a section of a multi-section tunable laser by finding the relative positions of modes in the laser. According to

25   the present invention the mode widths can be used to get mode modulation of a tunable laser.

Also it will be appreciated that by effecting a change in the gain current while measuring a power plane for a laser,

30   it is possible to compensate for power variation due to absorption in the passive sections of the laser.

The present invention additionally provides for the measurement of a plane which takes all of the above into account and compensates for the resulting in a measurement plane where either the relative size of modes is constant or the power jumps due to mode jumps are equalised.

The embodiments in the invention described with reference to the drawings comprise a computer apparatus and/or processes performed in a computer apparatus. However, the invention also extends to computer programs, particularly computer programs stored on or in a carrier adapted to bring the invention into practice. The program may be in the form of source code, object code, or a code intermediate source and object code, such as in partially compiled form or in any other form suitable for use in the implementation of the method according to the invention. The carrier may comprise a storage medium such as ROM, e.g. CD ROM, or magnetic recording medium, e.g. a floppy disk or hard disk. The carrier may be an electrical or optical signal which may be transmitted via an electrical or an optical cable or by radio or other means.

The invention is not limited to the embodiments hereinbefore described but may be varied in both construction and detail.

The words "comprises/comprising" and the words "having/including" when used herein with reference to the present invention are used to specify the presence of stated features, integers, steps or components but does not preclude the presence or addition of one or more other features, integers, steps, components or groups thereof.

Claims

1) A method of normalising the output values of a laser
   diode, the method comprising the steps of:

   a) varying the control currents for a specific section
      of a laser diode device over a range of values in a
      first sample index so as to obtain a set of output
      values for that section of the laser diode,

   b) normalising the set of output values; and

      wherein the normalisation of the output values
      compensates for non-linearities in the output values
      by effecting a change in relationship between the
      control currents and the sample index.

2) The method as claimed in claim 1 wherein the output
   values are representative of power or frequency.

3) The method as claimed in claim 1 or 2 further comprising
   the step of obtaining a set of normalised values for one
   or more further sections of the laser.

4) The method as claimed in claim 1 wherein the
   normalisation is effected by a transform applied to
   sample index, thereby changing the control currents and
   the output values.

5) The method as claimed in claim 4 wherein the transform
   is a non-linear transform.

6) The method as claimed in claim 4 or 5 wherein the generated transform is subsequently used to effect the further generation of a set of output values for multiple combinations of control currents or sections for the laser device, the generated set having being normalised due to the utilisation of the transform.

7) The method as claimed in claim 1 wherein the normalisation of the output values is effected using the current of the mode jumps.

8) The method as claimed in claim 7 wherein mode jumps are detected by a power measurement.

9) The method as claimed in claim 8 wherein the mode jumps are represented by discontinuities in a power measurement.

10) The method as claimed in claim 7 wherein mode jumps are detected by a frequency measurement.

11) The method as claimed in claim 8 wherein the mode jumps are represented by a step in a frequency measurement.

12) The method as claimed in claim 4 wherein the application of the transform effects an equalisation of mode width.

13) The method as claimed in claim 12 further comprising the step of determining deviations in mode width, thereby providing indications of the integrity of the laser device.

14) The method as claimed in claim 1 wherein the normalisation is effected using a relative loss of that section as a function of control current.

15) The method as claimed in claim 14 wherein the gain current of the laser device can be altered using said normalisation.

16) The method as claimed in claim 1 wherein the normalisation output values provides for a determination of location of modes.

17) The method as claimed in claim 16 further comprising the step of determining suitable operating points, the operating points being selectable on the basis of a determination of a mid-point in frequency values for a specific mode.

18) The method as claimed in claim 17 wherein the operating point is at the mean frequency for that mode and benefits from maximum side mode suppression.

19) The method as claimed in claim 16 wherein the mode are locatable by effecting a differentiating of the normalised values.

20) A method of determining a mode width for a laser diode device, the method comprising the steps of:

a) determining the location of the modes;

b) extracting from the determined mode locations, the mode width in control current as a function of a

control current for all modes and all currents so as to provide for a relationship between the mode width of the laser and a control current for that laser; and

c) converting the control current to frequency for the device so as to provide a relationship between mode width and frequency.

21) A method of obtaining the mode modulation for a laser diode, the method comprising steps of:

obtaining tuning characteristics of a tunable laser and measuring a set of sample data where this data has been normalised out;

detecting mode jumps of the tunable laser;

measuring a mode width of the laser and plotting this value against a predetermined combination of control currents for the tunable laser where this mode is present which can in turn be converted to output frequency of the tunable laser; and

converting the mode width to a percentage deviation of average mode width of the laser.

22) A computer program comprising program instructions for causing a computer to perform the method of any one of claims 1 to 21.

23) A computer program as claimed in claim 22 embodied on a record medium.

24) A computer program as claimed in claim 22 embodied on a carrier signal.

5   25) A computer program as claimed in claim 22 embodied on a read-only memory.

26) A control system for normalising the output values of a laser diode, the system comprising :

10

    means to vary the control currents for a specific section of a laser diode device over a range of values in a first sample index so as to obtain a set of output values for that section of the laser diode;

15

    means to normalise the set of output values; and

    wherein the normalisation of the output values compensates for non-linearities in the output values by

20   effecting a change in relationship between the control currents and the sample index.

27) The system as claimed in claim 26 wherein the output values are representative of power or frequency.

25

28) The system as claimed in claim 26 or 27 further comprising means for obtaining a set of normalised values for one or more further sections of the laser.

30   29) The system as claimed in claim 26 wherein the normalisation is effected by a transform applied to the sample index, thereby changing the control currents and the output values.

30) The system as claimed in claim 29 wherein the transform is a non-linear transform.

5   31) The system as claimed in claim 29 or 30 wherein the generated transform is subsequently used to effect the further generation of a set of output values for multiple combinations of control currents or sections for the laser device, the generated set having being normalised due to
10   the utilisation of the transform.

32) The system as claimed in claim 26 wherein the normalisation of the output values is effected using the current of the mode jumps.

15

33) The system as claimed in claim 32 wherein mode jumps are detected by a power measurement.

34) The system as claimed in claim 33 wherein the mode
20   jumps are represented by discontinuities in a power measurement.

35) The system as claimed in claim 32 wherein mode jumps are detected by a frequency measurement.

25

36) The system as claimed in claim 33 wherein the mode jumps are represented by a step in a frequency measurement.

37) The system as claimed in claim 29 wherein the
30   application of the transform effects an equalisation of mode width.

38) The system as claimed in claim 37 further comprising means for determining deviations in mode width, thereby providing indications of the integrity of the laser device.

5   39) The system as claimed in claim 26 wherein the normalisation is effected using a relative loss of that section as a function of control current.

40) The system as claimed in claim 39 wherein the gain
10   current of the laser device can be altered using said normalisation.

41) The system as claimed in claim 26 wherein the normalisation output values provides for a determination of
15   location of modes.

42) The system as claimed in claim 41 further comprising means for determining suitable operating points, the operating points being selectable on the basis of a
20   determination of a mid-point in frequency values for a specific mode.

43) The system as claimed in claim 42 wherein the operating point is at the mean frequency for that mode and benefits
25   from maximum side mode suppression.

44) The system as claimed in claim 41 wherein the mode are locatable by effecting a differentiating of the normalised values.

30
45) A control system for determining a mode width for a laser diode device, the system comprising :

means for determining the location of the modes;

means for extracting from the determined mode locations, the mode width in control current as a function of a control current for all modes and all currents so as to provide for a relationship between the mode width of the laser and a control current for that laser; and

means for converting the control current to frequency for the device so as to provide a relationship between mode width and frequency.

46) A control system for obtaining a mode modulation for a laser diode, the system comprising:

means to obtain tuning characteristics of a tunable laser and means to measure a set of sample data where this data has been normalised out;

means to detect mode jumps of the tunable laser;

means to measure a mode width of the laser and plotting this value against a predetermined combination of control currents for the tunable laser where this mode is present which can in turn be converted to output frequency of the tunable laser; and

means to convert the mode width to a percentage deviation of average mode width of the tunable laser.
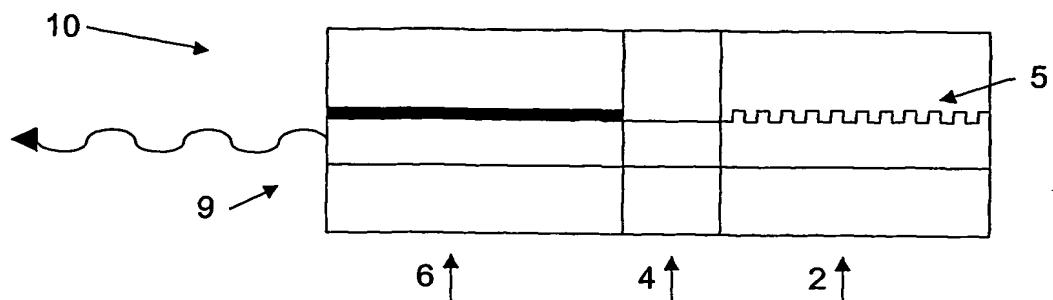
Figure 1

Figure 2

Figure 2a

Non-Linear Power Line

Power

Non Linear Mapping of Passive Section Current

Figure 2b

High Resolution Power Line

power

0.0   5.0   10.0   15.0   20.0   25.0   30.0   35.0   40.0   45.0   50.0   55.0   60.0   65.0   70.0   75.0   80.0

DBR Section Current (mAmps)
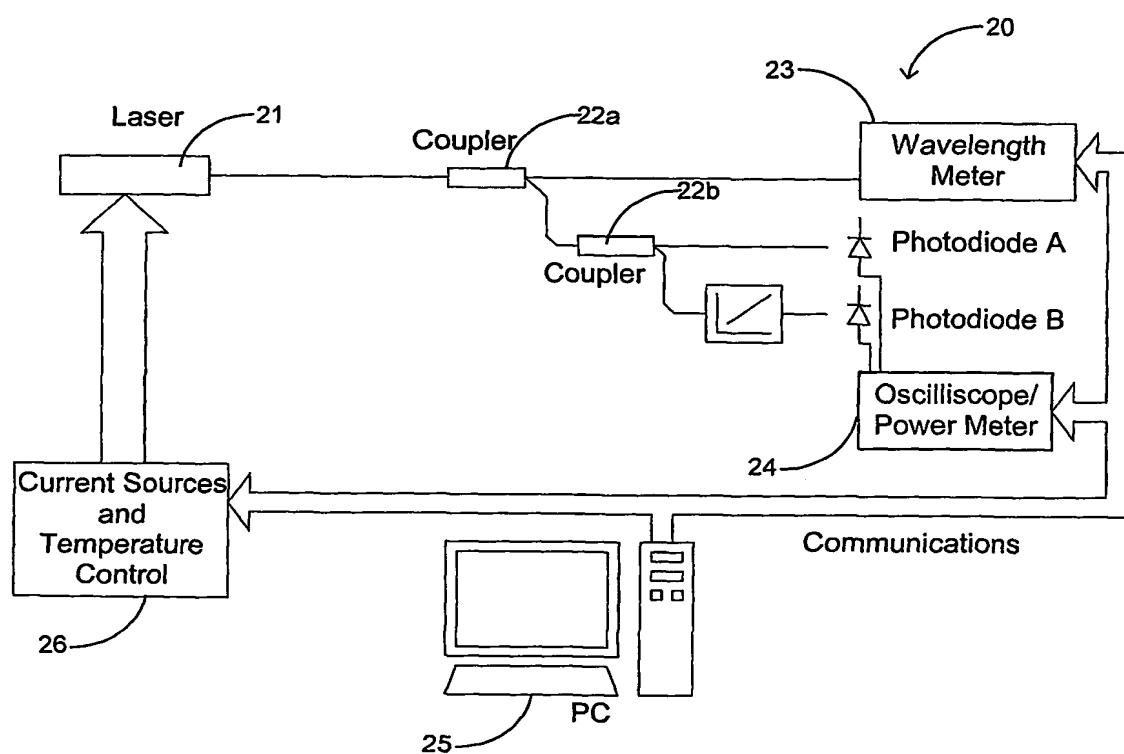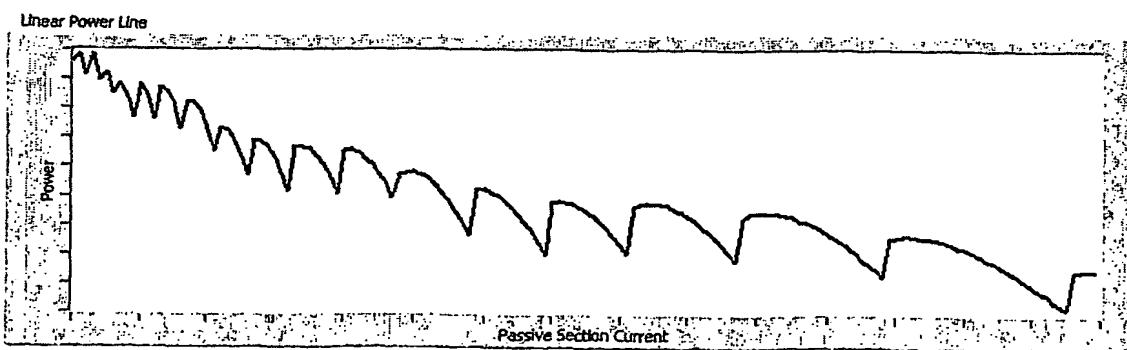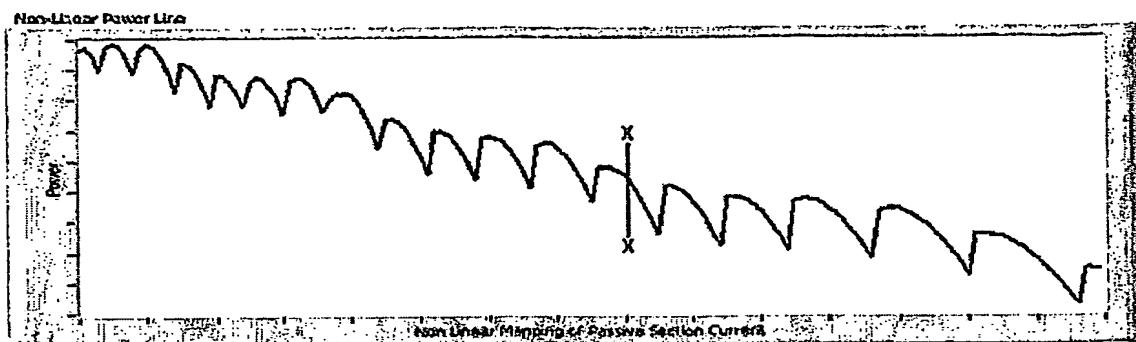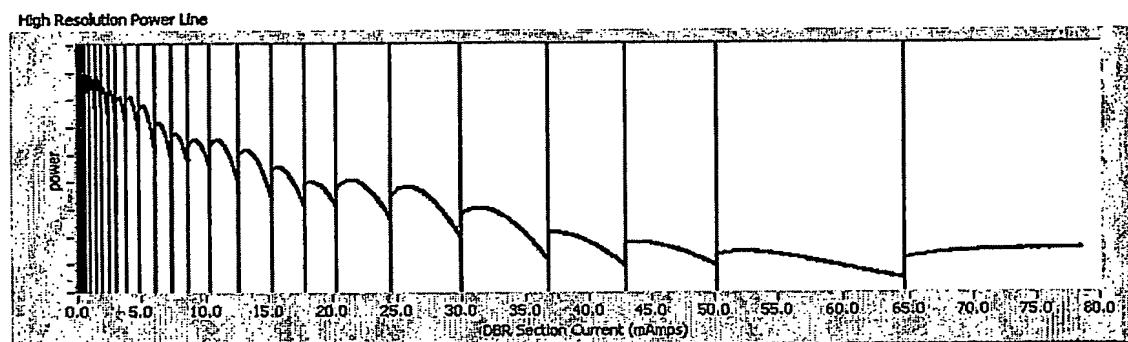
Figure 3

Plot of Bragg Current vs. Mode Index
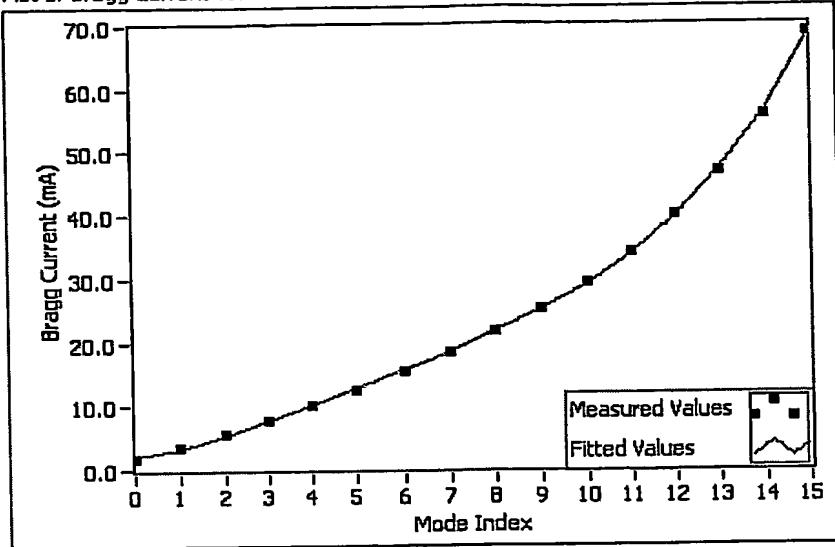
Figure 4

Plot of Bragg Current vs. Sample Index
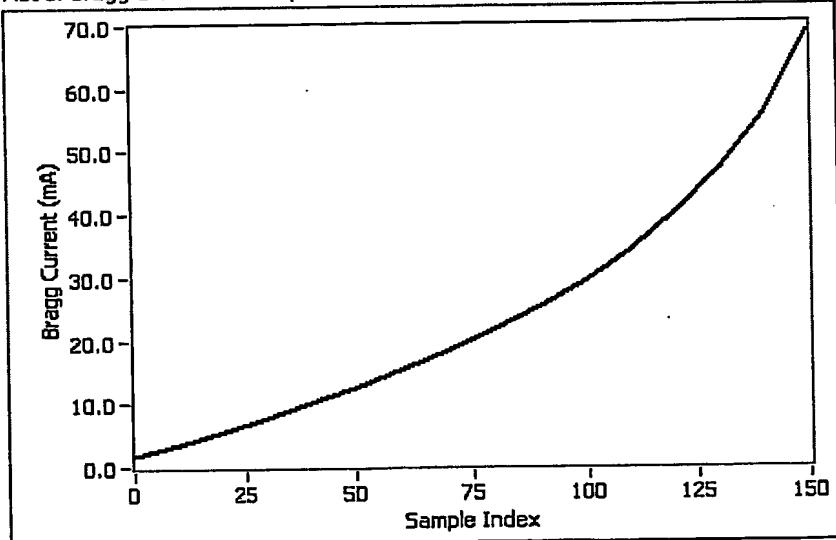
Figure 5

Linear Wavelength Plane of DBR Laser
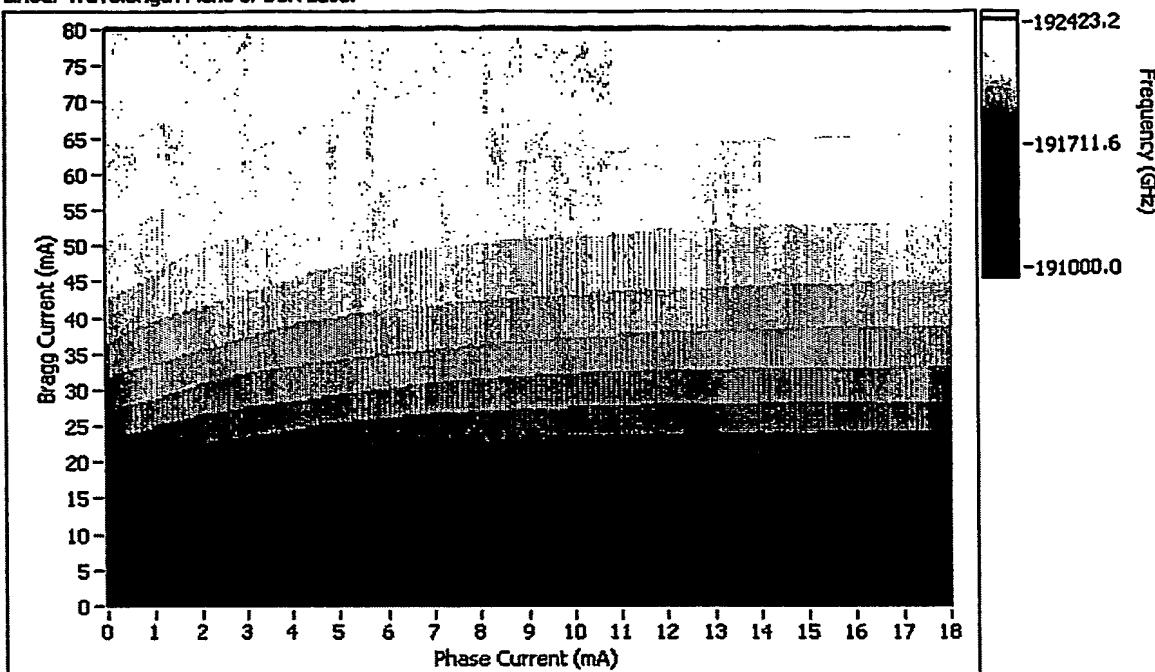
Figure 6

Non-Linear Wavelength Plane of DBR Laser
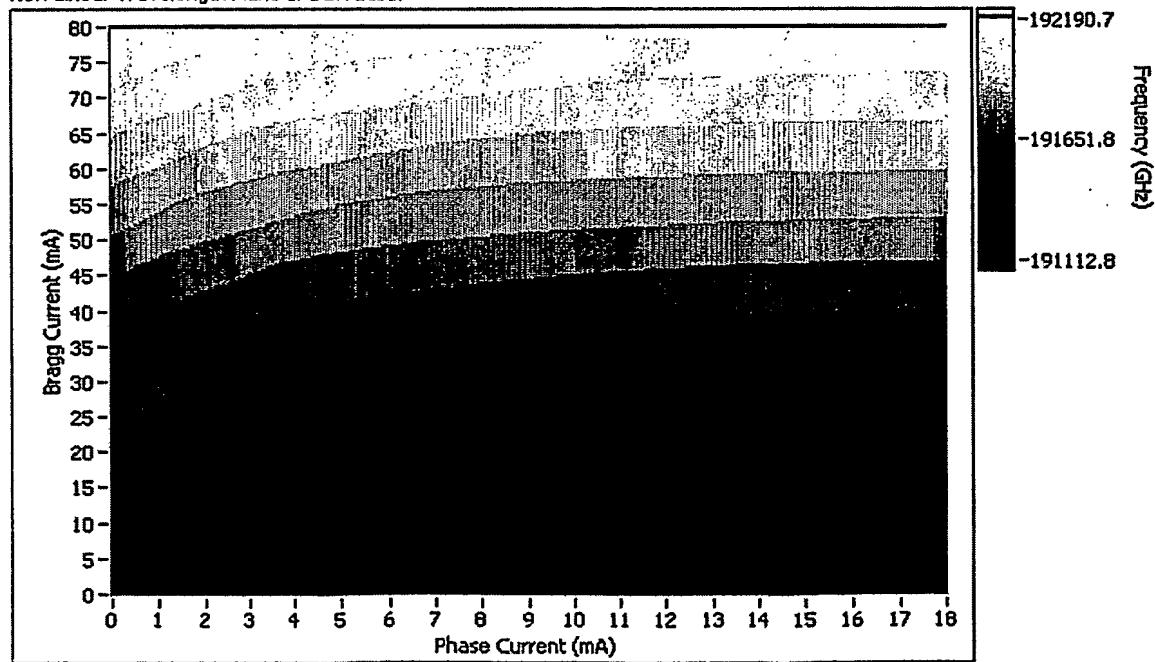
Figure 7

Plot of Mode Width vs Bragg Current (Laser with Mode Modulation)
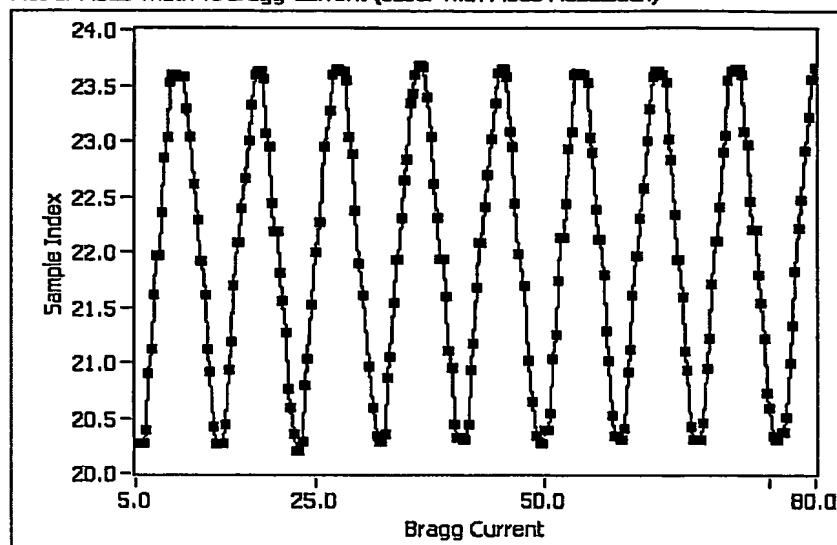
Figure 8

Plot of Mode Width Variation vs Frequency (Laser with Mode Modulation)
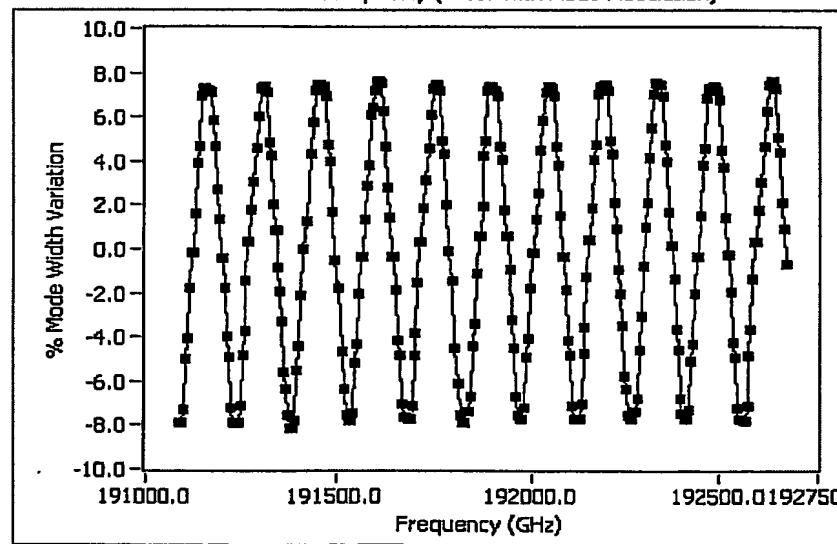
Figure 9

Frequency Modulation vs Frequency (Laser with Mode Modulation)
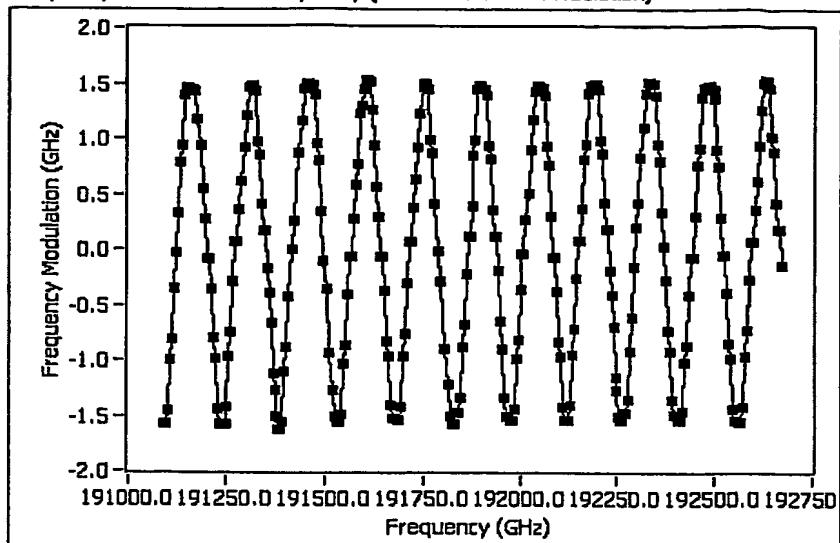
Figure 10
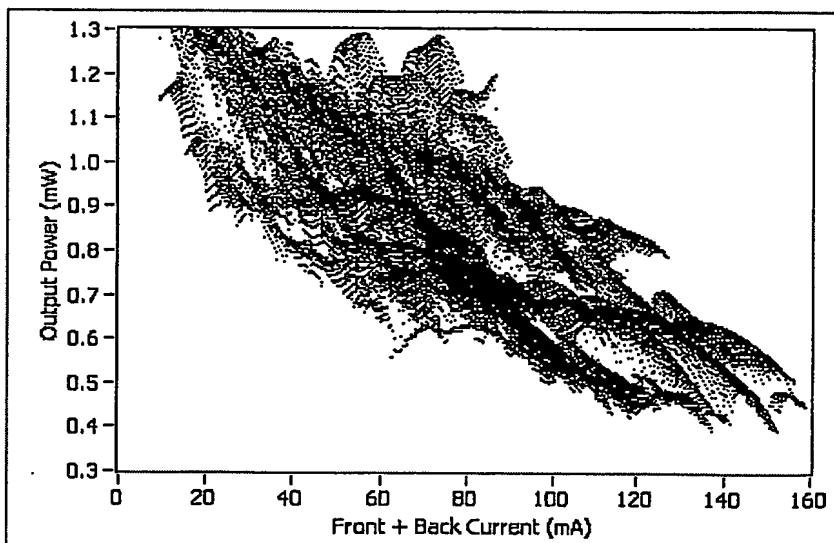
Figure 11
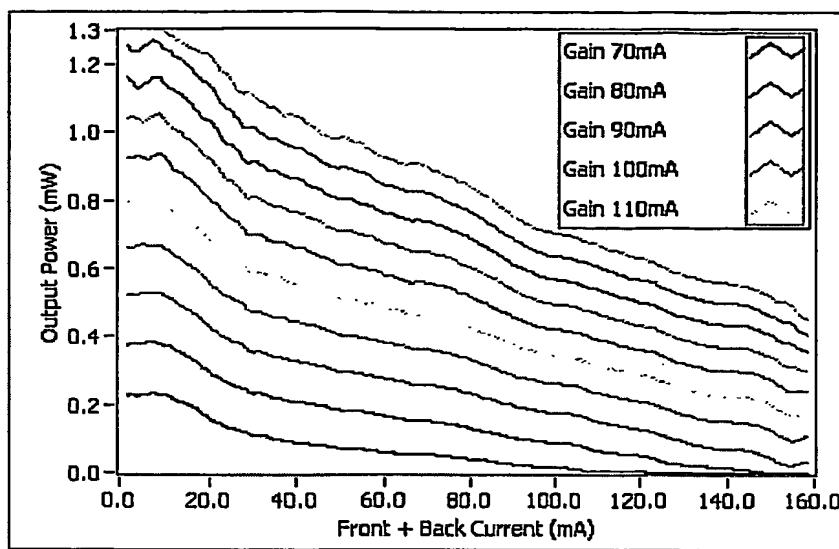
Figure 12
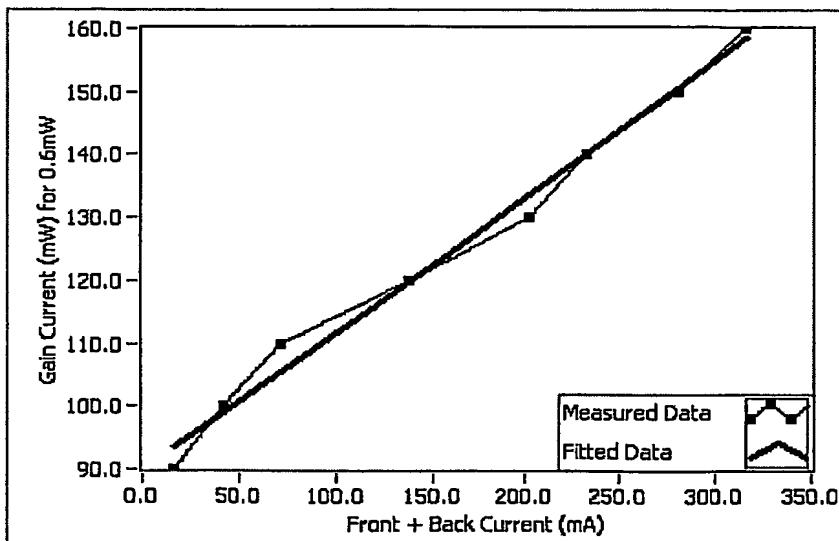
Figure 13
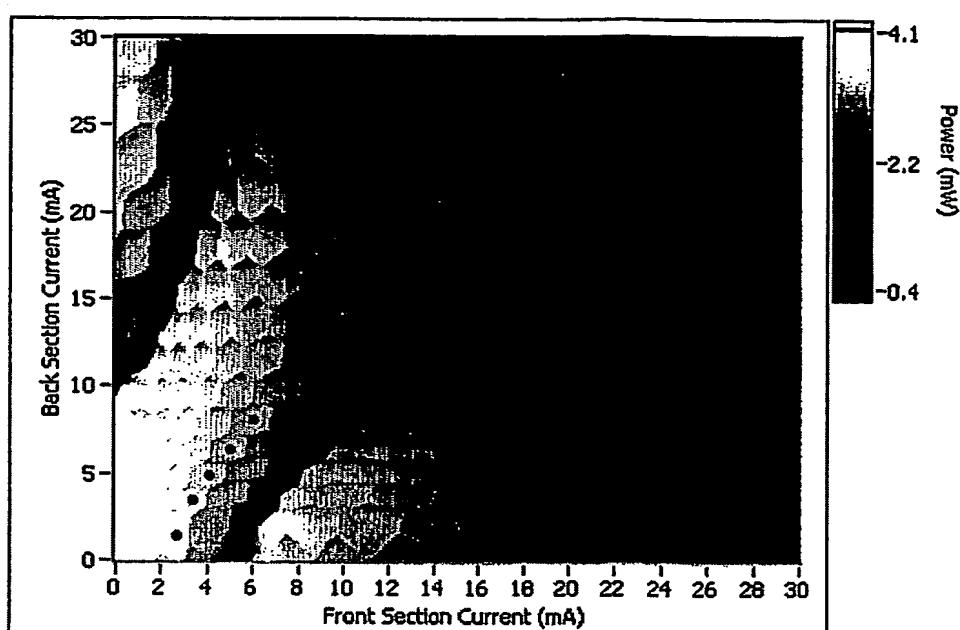
Figure 14
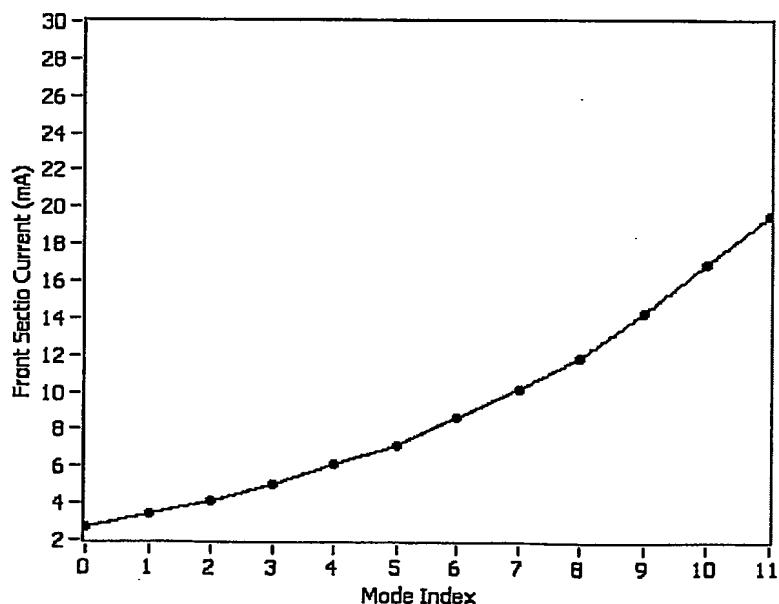

Figure 15
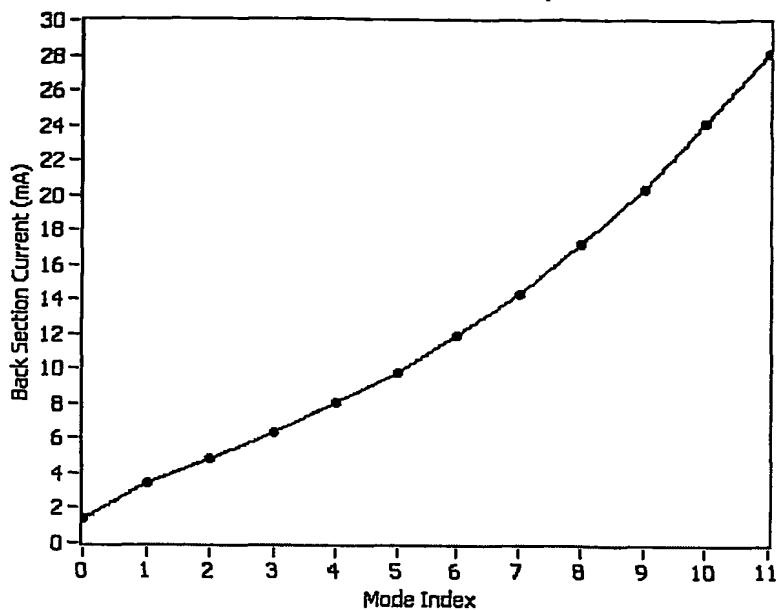
Figure 16

Plot of Mode Jumps of DBR Laser
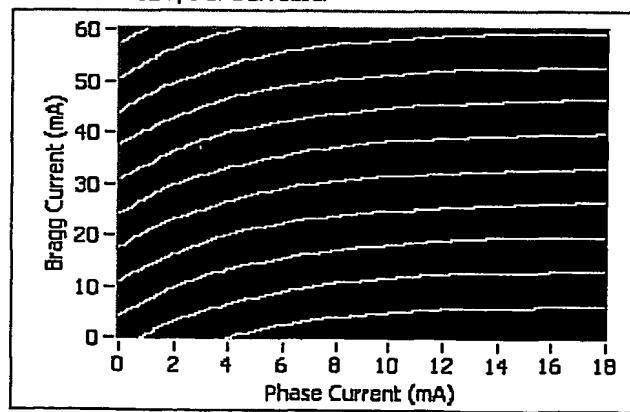
Figure 17

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7   H01S5/0625

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7   H01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC, COMPENDEX, IBM-TDB

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	SARLET G ET AL: "CONTROL OF WIDELY TUNABLE SSG-DBR LASERS FOR DENSE WAVELENGTH DIVISION MULTIPLEXING" JOURNAL OF LIGHTWAVE TECHNOLOGY, IEEE. NEW YORK, US, vol. 18, no. 8, August 2000 (2000-08), pages 1128-1138, XP000989390 ISSN: 0733-8724	1-19, 26-43
Y	page 1135, left-hand column -page 1136, left-hand column; figures 6,15,18 page 1129, right-hand column, paragraph 2 -page 1131, left-hand column, paragraph 1	21,46

-/--

| X | Further documents are listed in the continuation of box C. | | X | Patent family members are listed in annex. |

° Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
13 January 2004	21/01/2004

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Laenen, R

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Y	page 148	21,46
A	WO 99 40654 A (ALTITUN AB ;ANDERSSON LARS (SE); BROBERG BJOERN (SE)) 12 August 1999 (1999-08-12) page 4, paragraph 2 -page 7, paragraph 2; figures 3,6	8-11, 33-36
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A	DELORME F: "WIDELY TUNABLE 1.55-MUM LASERS FOR WAVELENGTH-DIVISION-MULTIPLEXED OPTICAL FIBER COMMUNICATIONS" IEEE JOURNAL OF QUANTUM ELECTRONICS, IEEE INC. NEW YORK, US, vol. 34, no. 9, 1 September 1998 (1998-09-01), pages 1706-1716, XP000781930 ISSN: 0018-9197 the whole document	1-11, 26-36

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